

# Contraves Space



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# **Optical Ground Station**



# **Summary Report**

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#### 1 Introduction

The scope of this study was to propose modifications to the OGS such that it can participate in other missions than SILEX, e.g. LEO, MEO, moon, L1, L2 or deep-space, primarily in forthcoming international missions.

#### 2 **Review of OGS Technical Status**

# 2.1 The Optical Ground Station

ESA has constructed an Optical Ground Station (OGS) on the Canary Islands as part of the SILEX programme. The OGS will be used for commissioning and routine checkout of the ARTEMIS satellite and simultaneously receive and transmit data. The OGS is located at the Observatorio del Teide at Tenerife, situated at an altitude of 2.393 m, well above the first inversion layer or cloud level. The site offers optimal conditions for Earth to space optical communications links. The station consists of a one meter Ritchey-Chretien/Coudé telescope in a domed observatory building with all the associated control systems.

The OGS transmitter uses a Ti:Sapphire laser pumped by a 28 Watt Argon laser. The wavelength of the Ti:Sapphire can be automatically set between 750 nm and 900 nm.

For the SILEX experiment the wavelength of the Ti:Sapphire is tuned to 847 nm, where the laser's output power is some six Watts. A new laser transmission technique will be used by producing four incoherent sub-aperture beams which result in a more consistent signal received by the target.



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# **2** Review of OGS Technical Status

# **OGS** Optical Ground Station



## 2.2 Dome and Shutter

- Dome rotation speed: 0 180 mm/s (0 1.5°/s)
- Slit width: approx. 3.6 m
- Slit height: a) 0° 65° lower shutter open b) 40° 105° upper shutter open
- slit reconfiguration time: approx. 6 minutes

# **2** Review of OGS Technical Status

# OGS Optical Ground Station

# 2.3 Telescope - Coudé System

- clear aperture:
- unvignetted FOV:
  - (2.4 mrad) tion: 10<sup>-6</sup> μrad

1 m

8 arcmin

angular resolution:



# 2.4 Optical Bench / Pointing Mechanisms

Fine Pointing Mirror

- deflection range:
- +/- 5 arcmin (+/- 1.45 µrad)
- angular resolution:
- 0.01 arcsec (0.05 µrad) 400 Hz
- bandwidth:
- Transmit Pointing Mirror
- angular range:
- angular accuracy:

+/- 27 arcsec (+/- 130 µrad) 0.05 arcsec (0.24 µrad)



# 2.5 Laser Transmitter Characteristics - OGS to ARTEMIS

- Nominal wavelength:
- Effective divergence cone angle (1/e<sup>2</sup>): 12.8 arcsec (64 µrad)

847 nm





# 3 LINK PROBABILITY ANALYSIS

Cloud data on a global scale were analysed to predict link probablities. Networking of several stations in meteorological uncorrelated sites may improve the link probability considerably.

#### 3.1 ISCCP cloud data

ISCCP is the International Cloud Climatology Project. The data are derived from geostationary satellites (American GOES, European METEOSAT, Japanese GMS and sparsely of the Indian INSAT) and polar orbiting (NOAA + Tiros-N) meteorological satellites. The D2 type data report monthly means for 3 h intervals over 11 years, from 1983 to 1994. The detect channels for clouds are in the visible and thermal infrared. The lowest cloud coverage is found in the subtropics, usually above desert land surfaces. The average for the Canary islands was found to be approximately 40% which is too high for the OGS, because the ISCCP data are from a 280 km equal-area grid and do not consider the OGS height above the inversion layer.



ISCCP-D2 11-year Mean Annual

Fig. 3-1 Longterm average of cloud cover from ISCCP data.

# 3.2 METEOSAT cloud data

Cloud coverage with a spatial resolution of approximately 16 x 20 km<sup>2</sup> was derived from Meteosat data for the extended mediterranean area. The datasets cover 365 days with 48 half hourly images per day over whole year of 1998). The cloud index was derived from the visible (VIS) and infrared (IR) image channel. The mean value for the Canary Island Tenerife is 0.30, which would give a link probability of 70%.







Fig. 3-2: Mean probability of clouds for 1998.

#### 3.3 Synop Station Izaña

Data from the closeby synop station Izaña (2 km eastward of the observatory at an altitude of 2367 m a.s.l.) indicates lower cloud coverage: The yearly sunshine hours are given with 3700 h, which results in a cloud coverage of approximately 16% at daytime. The site at the slope of mount Teide is high above the trade wind inversion. Much of the cloud coverage seen by the METEOSAT data should be at lower levels.

#### 3.4 Cloud correlation distance

The radius of the strongly correlated area is approximately 500 km as can be seen from analyses of two stations, one in Sardegna, the other in Egypt.



Fig.3-3: Relative conditional cloud cover for a 2-station network along a W-E cross-section through Sardegna.

# 3.5 Network of several stations

The combined link probability of meteorologically uncorrelated stations is given by

$$P(n) = 1 - \prod_{i=1}^{n} P(C_i),$$

Combining two stations with a fully uncorrelated mean cloud coverage *C* of 20% we derive a combined link probability  $P_{atm}$  of 96%, connecting three of such stations results in  $P_{atm}$  = 99.2%.

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# INTERNATIONAL DEVELOPMENTS AND TRENDS

Seasonal variations of cloudiness in the subtropics are in the order of 10% absolute cloudiness. As the annual cycles in northern and southern subtropics are complementary this results in an appreciable increase of  $P_{atm}$ , if northern and southern stations are combined: The 2-station network of fully independant stations with annual average cloud cover of 20% ± 10% results in  $P_{atm}$  = 97% instead of 96% for the estimate neglecting seasons. Placing both stations on the same hemisphere leads to a stronger annual cycle of combined link probability: 91% in the less favoured season, but 99% in the better one.

# 4 INTERNATIONAL DEVELOPMENTS AND TRENDS

NASA's optical communication programme is closely connected with the long term deep space exploration program, mainly concerned with the downlink from satellites to the Earth, because downlink capacity is a critical issue. Currently, an experimental optical ground station is being built on Table Mountain in Southern California and there are plans to deploy several large optical ground stations of the 10-m class.

Japan followed the development of ESA and NASA for optical communication in space and has developed own optical link equipment, covering both fields, i.e. space-space and space-ground. A Japanese ground station was built in 1988 at Koganei, Tokyo by CRL.

The space-to-ground links under investigation are based on following wavelengths:

USA/NASAMPL:

- OCD with 1550 nm
- X2000 transceiver with 1064 nm Tx

Japan/NASIDA/CRL:

• LCDE with 1552 (Tx) and 1562 (Rx) nm

# 4.1 The Mars Internet

The nearest candidate for intensive exploration is identified to be the mars, and thus a challenging communication concept is developed. The program foresees the deployment of a cluster network of low orbiting Microsats for routing data from Mars probes to the Earth.



Fig.4-1: The planned Mars Network



The link capacity shall be approximately 11 kbps between the Microsatellites and about 1 Mbps data return from the relay satellite MARSAT to the Earth. The deployment shall be performed in the years 2003-2009 and shall support Mars probe activities including robotics. HDTV level (34 Mbps) shall be reached from or beyond 2010 assuming fully operational optical communication".

# 4.2 NASA Deep Space Communication Program

Analysing the planned missions against the current WN capabilities resulted in an overbooking of the WN facilities by 60% already in the year 2005. The plans for development of new technologies with the purpose to increase the link capacity are summarised in NASA's Deep Space Telecommunications Road Map, which was developed in 1998. Three fields of technology are promoted: X-Band communication, Ka-Band communication and optical communication.



The roadmap for optical communication up to 2010 is shown in the figure below.

In order to

highlight the potential of the two fields of development (Ka-Band and optical), NASA has proposed a new metric which considers the amount of data which can be downlinked over a given distance (and in a given time of antenna availability - TW). For this purpose, NASA defines a "reference spacecraft" with the following properties:

	RF system	Optical system (X2000 transceiver)
Output power	10 W	3 W
Antenna aperture	1 m	300 mm <sup>1</sup>

The link capacity in Megabytes, assuming a link window of 5 hours, to be reached for several missions and two classes of ground stations is listed in the table below:

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<sup>&</sup>lt;sup>1</sup> This was the baseline for the X2000 transceiver. Meanwhile, the host platform for the X2000 has been changed, and the X2000 transceiver is continued with a 100 mm aperture.



	X-B	and	Ka-Band		Optical $\lambda \sim 1064$ nm	
Ground	34 m	70 m	34 m	70 m	1 m	10 m
Antenna						
Mars	182.6	727.5	659.6	1772.1	29.5	2151.3
Jupiter	42.2	168.2	152.5	409.6	6.8	497.3
Saturn	12.5	49.9	45.2	121.4	121.4	147.4
Pluto	0.7	2.9	2.6	7.1	7.1	8.4

## Table 4-1 : Link capacity for different technologies and different ground antenna size.

The advantage of the Ka-Band use is roughly a factor of three compared to the use of the X-Band, but only if NASA will succeed to deploy 70 m antennas. Otherwise, the capacity of the new 34 m Ka-Band antenna at Goldstone is almost the same a for a 70 m X-Band Antenna.

On the other hand, a 70 m Ka-Band antenna would almost reach the capacity of the aimed optical link, bringing the optical technology into a strong competition with a more conventional and mature technology. NASA's roadmap foresees the implementation of three 70 m Ka-Band antennas between 2006 and 2009, and the "need" for an earlier availability of an optical link with a 10 m ground antenna must be seen in this context. In its technology roadmap, NASA does not highlight this competitive situation, but presents the two technologies as complementary development potentials.

## 4.3 NASA Near-Earth communication opportunities

All plans and proposals mentioned here consider a downlink to a 1 m receiver ground station.

## 4.3.1 ISS

An optical link has been proposed between the ISS and the OCTL. The ISSERT has sponsored the upgrade of the OCD to the 0WHRLF, so there is a certain confidence that this terminal will be installed when the OCDHRLF has reached flight readiness level. The design of the space terminal shall be based on the OCD development and will have an aperture of 100 mm. The downlink shall provide 2.5 Wps for a distance of 985 km at a Tx power of 200 mW. The operating wavelength is chosen to be the eye-safe 1550 nm wavelength.

Fig. 4-3:	Proposed accommodation of
OCDHRL	F on the ISS

Link Distance	985 km
Data Rate	2.5 Gbps
Tx wavelength	1550 nm
Tx power	200 mW
Tx aperture	100 mm
Tx modulation	OOK
Ground reception	1 m Antenna (OCTL)
Planned	2003
Ground reception Planned	1 m Antenna (OCTL) 2003





# **Optical Ground Station**

#### 4.3.2 Shuttle

The link to the shuttle is very similar to the ISS downlink, except that the downlink capacity is increased by a factor of four to 10 GBps by introducing 4 x WDM with a 10 nm spacing. The Tx power is 4 x 200 mW. A mass budget is assumed with 62 kg. The project runs under the name FOCAL.

The major purpose of this experiment is likely the demonstration of a multiplexer working at the spacecritical 1550 nm with Erbium technology. It's the advantage of the shuttle that such experimental payloads do not require a long lifetime and parts can be exchanged between the missions.

Link Distance	?
Data Rate	4 x 2.5 Gbps
Tx wavelength	1550 nm
Wavelength spacing	10 nm
Tx power	4 x 200 mW
Tx aperture	100 mm
Tx modulation	?
Ground reception	1 m Antenna (OCTL)
Mass	62 Kg
Planned	?

## Fig. 4-4: Proposed allocation of FOCAL on the STS



#### 4.3.3 **ARISE** mission

ARISE stands for Advanced Radio Interferometry between Space and Earth, a NASA VILBI program. ARISE will be a mission consisting of one (or possibly two) 25-meter inflatable radio telescopes in a high elliptical Earth orbit. The telescope(s) would observe in conjunction with a large number of radio telescopes on the ground, using the technique of space Very Long Baseline Interferometry (VLBI), in order to obtain the highest resolution (10-microarcsecond) images of the most energetic astronomical phenomena in the universe.

# Fig. 4-5 : Artists impression from the ARISE mission

This space interferometer is planned to be launched in 2008 and shall fly on a HEO between 5.00 and 40.00 km. The program has identified a need for a high data rate and therefore considers also to establish an optical downlink.

The transceiver shall provide a downlink of 8 Gbps in 4 WDM channels. The operating wavelength shall be 1550 nm.



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The terminal looks like an upgrade of the FOCAL instrument. Two parameters shall be increased:

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- Increase of the Tx aperture to 150 mm or possibly 200 mm
- Increase of the output power to 5 W.

The most critical component is identified to be a space qualified multiplexer. This component is planned to be tested with the FOCAL experiment on the STS.

The link is designed to use as receiver a 1 m ground antenna.

Link Distance	5.00 - 40.00 km HEO
Data Rate	8 Gbps
Tx wavelength	1550 nm
Wavelength spacing	10 nm
Tx power	5 W
Tx aperture	150 mm (possibly also 200 mm)
Tx modulation	?
Ground reception	1 m Antenna (OCTL)
Planned	2008

#### 4.4 Japanese Optical Communication Programme

The free space optical communication program in Japan is settled at two organisations: The NASDA and the CRL. Since CRL acts as the prime contractor of the NASDA LCDE terminal.

Currently, two optical terminals are under development:

- LUCE on OICETS complementing the SILEX program
- LCDE for the ISS

## 4.4.1 LUCE on OICETS

The Laser Utilising Communications Experiment LUCE will complement ESA's SILEX experiment and will establish two links:

- To the SILEX payload on the geo-stationary Artemis satellite
- To the CRL optical ground station at Koganei (feasibility studied).



# Fig. 4-6 : Link Scenario for OICETS

The launch is foreseen on the Japanese J-1 launch vehicle in 2001.

A link to the ESA optical ground station is not foreseen.



## 4.4.2 Laser Communications Demonstration Experiment (LCDE) on the ISS

The LCDE shall be placed into one payload slot of the Exposed Facility (EF) at the Japanese Experiment Module (JEM) Kibo and shall establish an experimental 2.5 Gbps link to a ground station.



#### Fig. 4-7: The Japanese Experiment Module Kibo

Fig.4-8 shows a 10 Gbps optical link from a data relay satellite to a "Ground station with adaptive optics". This addresses likely the transfer of the originally planned optical link at the Japanese Gigabit Satellite (2 Gbps) to the Advanced DRTS satellite. No further details about this plan are known so far.

Unfortunately, the LCDE has been specified has a multifunctional device which shall perform:

- Optical communication
- Laser ranging and tracking (space debris)
- Imaging (space debris)

In the development, this has caused an overloading of the LCDE with concurrent requirements concerning spectral range (400 ... 1550 nm (!) for the front end optics), hard WFE requirement over a larger FOV ( $\pm 0.3^{\circ}$ ), wide pointing range and limited telescope accommodation frame, and consequently technical and financial problems and of course schedule delay. The specified aperture of the telescope has recently reduced from 150 mm to 130 mm and an ITT is currently issued world wide.

Link Distance	Ca. 1000 km (?)
Data Rate	
<ul> <li>Downlink</li> </ul>	2.48832 Gbps
<ul> <li>Uplink</li> </ul>	1.24416 Gbps
Tx/Rx aperture size	130 mm
Central Obscuration (diameter)	< 0.25
Tx wavelength	1552 nm
Rx wavelength	1562 nm
Tx output power	400 mW (EDFA)
Wall plug power	115 W
Mass	< 90 Kg



# 5 LINK BUDGET

#### 5.1 Algorithms

To assess the potential performance of the ESA optical ground station for future space-toground communications scenarios, not only the ground station itself, but also the atmosphere above has to be taken into account. Due to turbulence, the optical power incident on the opto-electronic receiver will not be a well-known measure, but rather a statistical quantity. Unfortunately, the bit-error probability (BEP) for practically every modulation format varies significantly with the received optical power. It is therefore necessary to use statistical methods to evaluate the link performance.

As link performance criterion, we thus chose the *data rate* that is achievable for a given BEP, where the BEP (not the received power) is averaged over a representative number of statistical realizations of the atmosphere.

Figure 1 shows the block diagram of the link budget analysis tool developed.



#### Fig. 5-1: Block diagram of the link budget analysis tool developed

#### 5.2 Results

We have developed a link budget analysis tool predicting the performance of optical spaceto-ground and ground-to-space communication links in terms of achievable data rate (for a given bit error probability). The influence of signal fading due to atmospheric turbulence is taken into account using a Monte-Carlo simulation method. Various combinations of detector type (single-mode or multi-mode), receiver type (avalanche photo diode, optical pre-amplifier & p-i-n photo diode, or coherent receiver), and modulation format (on-off keying, pulse position modulation, or phase-shift keying) are considered.

The model has been verified by analyzing the link between the OPALE terminal on board the ARTEMIS satellite and the ESA Optical Ground Station (which should be operational

very soon), and comparing the results with those of previous studies. The link margins obtained in both cases match very well.

Investigations on possible communication links between the International Space Station and the ESA Optical Ground Station quickly revealed, that the optical power budget is certainly not the limiting factor for the data rates envisaged today (several Gbit/s).

As a representative example for deep-space communications, a downlink from Mars to the ESA Optical Ground Station has been analyzed. With a transmit power of 1W (at 1064nm) and a transmit telescope diameter of 10cm, data rates between 1kbit/s (on-off keying with return-to-zero pulses) and 10kbit/s (pulse-position modulation) could be achieved, if direct-detection receivers were used and the Earth-Mars distance were 88 million km (i.e. close to its minimum). For the maximum Earth-Mars distance (about 400 million km), the data rates achievable (during nighttime only) would be several 100bit/s.

To improve this situation, one could, for example,

- increase the transmit power and/or the transmit aperture diameter,
- increase the receive aperture diameter (i.e. build a new telescope), or
- use phase-shift keying, in combination with an adaptive optics system and a coherent receiver (relatively low complexity in the deep-space transmitter, but very high complexity on ground). Depending on the performance of the adaptive optics system, the data rate could be increased by a factor of up to 10 (in comparison with pulse-position modulation).

# 6 Pointing, Acquisition and Tracking

## 6.1 Assessment of possible scenarios

The possible scenarios for an optical downlink are:

- the ISS as an example for an LEO satellite,
- the Artemis as an example for an GEO satellite,
- the Arise mission as an example for an HEO satellite and
- a Mars probe as an example for a deep-space probe.

#### 6.1.1 LEO satellites

The maximum azimuth rate during an ISS passage is 4.8 deg/sec and the maximum elevation rate is 0.53 deg/sec. However, these angular rates are not required for every link.

The OGS is not very well suited for LEO tracking but it is possible with constraints on the pointing accuracy. Up to 8 minutes link duration can be expected to the ISS with dome rotation speed below 1°/sec (max. dome rotation is 1.5°/sec) and elevation speed not exceeding 0.1°/sec.

# **6** Pointing, Acquisition and Tracking

# OGS Optical Ground Station



Fig. 6-1: ISS-to-ground-link (only lower dome slit open) Fig. 6-2: Duration of ISS-to-ground-link (only lower dome slit open)

## 6.1.2 HEO satellites



As an example for HEO satellites the Arise mission will be taken into consideration.



The mean duration is 11970 seconds during the two days, which have been assessed. The total duration is 83790 seconds, which means that a link is possible almost half of the time of a day.

The maximum elevation for the Arise-to-ground-link is 89.971 deg. However, the mean elevation is 29.3 deg. Thus also the Arise-to-ground-link is rather shallow and will be disturbed by the atmosphere, too. The maximum range is 25640 km and the mean range is 18082 km, i.e. a link from the OGS to the Arise satellite in the first orbit is shorter than a link to a geostationary satellite.

## 6.1.3 Deep space missions

As an example for a deep-space link a mars-to-ground-link has been assessed. The link has been dated for the 31.03.01 and the 01.04.01.



Fig. 6-5: Distances from Earth to Mars and apparent diameter of the Mars



Fig. 6-6: Distances from Earth to Mars

The evaluation of the tracking and pointing has shown that a possible terminal for a Mars mission would track on the Earth image. That means for the OGS, that no uplink beam is required for tracking and the OGS can track on the downlink beam and use this as pointing reference. However, the OGS has been optimised for operation with GEO terminals and has not a sufficient link margin for tracking, i.e. the downlink signal from the Mars terminal is

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very faint. This could be overcome by a modification of the optical bench or of the tracking method, i.e. stars or the Mars itself may be used as tracking references.

## 6.2 Summary of Pointing, Acquisition and Tracking

Starting from an assessment of the ground and space segment this study has analysed the different possible terminals and missions, which are planned for future optical space-toground communication. The ESA optical ground station at the Izaña on Tenerife was the focal point of this study.

In principle this study led to the conclusion that the PAT S/S of the OGS is already capable for a communication with geostationary satellites because the OGS has been designed for a check-out of the Artemis satellite, which is in-fact a geostationary satellite. Also HEO satellites are not a problem, if the angular motion is not too high. The communication with LEO satellites, however, is a problem, because the telescope has to be moved fast in order to track such a satellite. This corresponds to a decrease in the tracking accuracy of the telescope thus the LEO satellite, as assessed at the example of the ISS as most interesting target, can not be tracked. Astonishingly, the limited speed of the dome and the obscuration of the dome shutter are not a major concern for ISS-to-ground links.

For deep-space missions there are two different types of missions on the horizon, which carry equipment capable for optical communication, a Mars mission from then NASA and the SMART-1 mission from the ESA. The NASA missions are based on the X2000 terminal for optical communication, while the SMART-1 mission shall be used for a link experiment with a CCD-imager.

The commonness between these two DS-missions is that both missions do not utilise a beacon on the space segment. In other words the OGS has to be capable to acquire the probe without any optical feedback from the probe. Hence the position of the probe has to be known to the accuracy of the angle of the beam divergence for acquisition, at least for the SMART-1 mission. The X200 terminal will be capable to direct the downlink laser autonomously towards the groundstation, which has to acquire it. The acquisition of LEO, GEO and HEO satellites is rather simple, because a beacon acquisition can be utilised.

Also the pointing to and the tracking of a LEO, HEO and GEO satellite is quite simple, with the exception of the high angular motion of the LEO satellite. The tracking of a Mars probe is not such easy with the current equipment of the OGS because the received signal-power is not sufficient enough to track the downlink signal from the Mars.

INTERNATIONAL PROJECTS

# **OGS** Optical Ground Station

# 7 INTERNATIONAL PROJECTS

# 7.1 The Present Lasercom Experiments



# ESA:

Programme <u>SILEX</u> 1. ARTEMIS to SPOT 4 Tx = 830 nm, Rx =  $810\pm$  nm 2. OGS to ARTEMIS Tx = 847 nm, Rx = 750 - 900 nm

# NASA:

Programme <u>OCD</u> 1. STS to OCTL (TMF) Tx = 844 nm, Rx =  $780\pm$  nm

# NASDA:

Programme <u>LUCE</u> Tx = 843 - 853 nm, Rx = 815 - 825 nm 1. TACC (CRL) to OICETS 2. OICETS to ARTEMIS

The European and the Japanese programs are linked via

ARTEMIS and OICETS. Laser diode wavelengths in the range between 780 nm and 870 nm are used for all current programs. As for OCTF, it is planned to change very quickly from 800 nm to 1550 nm, the preferred wavelength for future LEO links (STS, ISS).

# 7.2 Missions in Preparation

# USA: NASA/JPL

The next step at NASA is a communication downlink from the ISS to the OCTL on Table Mountain. The downlink will operate at 1550 nm with 4 optical channels in wavelength division multiplex operation; an uplink beacon of 980 nm will be provided by OCTL as pointing reference. This experiment is an extension of the running OCD (Optical Communication Demonstrator) and is named OCDHRLF(OCD High-Rate Link Facility).

• OCDHRLF downlink with 1550 nm

## Japan: NASDA/CRL

NASDA intends to implement an own optical terminal on the Japanese Experiment Module (JEM) at the ISS. A bidirectional link of 2.5 Gbps capability between ISS and the optical

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# INTERNATIONAL PROJECTS

# **OGS** Optical Ground Station

ground station at Koganei (near Tokyo) shall be established. The communication wavelength again is 1550 nm; a beacon of 680 nm is used as pointing reference. The project is called LCDE (Laser Communication Demonstration Equipment).

LCDE uplink and downlink with 1550 nm

The near future US and Japanese programs are to the ISS, both use the eye-safe 1550 nm wavelength.



# Europe: ESA

In the present ESA planning there is no near- or mid-term optical communication mission beyond SILEX. But there are two opportunities to use the existing OGS and to extend the laser communication experiment beyond ARTEMIS:

- AMSAT P3-D (which is equipped with a 835 nm diode laser) and
- SMART-1 (which is equipped with a CCD camera and a dedicated focal plane filter)

## Rationale for a communication link with AMSAT:

The attractivity of AMSAT P3-D is that the satellite can transmit a pulse-coded (OOK) laser signal at 1600 Hz, synchronous with the 400 bit/s BPSK telemetry signal at 2.4 GHz. A communication link to OGS would enable ESA to evaluate the BER (bit-error-rate) from space to ground under real conditions. Although the atmospheric effects for optical downlinks have been measured and analyzed before, little experimental data is available for BER.

## Rationale for laser link to SMART-1:

The attractivity of SMART-1 is that the influence of the atmosphere for uplinks can be measured for various elevation angles and different S/C distances. ARTEMIS allows the determination of atmospheric effects only for a fixed elevation angle.

# INTERNATIONAL PROJECTS



# 7.3 Planning for the Future

Optical space communication is in hard competition with the well-established microwave communication. Presently, two applications offer sufficiently advantages over microwave communication that further developments appear to be justified.

(1) Intersatellite optical links between LEO satellites and an interorbit optical link to a relay satellite in GEO (or several relay satellites in MEO)

Optical intersatellite links in LEO have been extensively studied and developments have been undertaken for broadband space communication programs (e.g. TELEDESIC). The commercially oriented programs are on hold now due to the Iridium disaster, and the uncertainty about the business success of Globalstar. Optical ground stations for this kind of commercial optical communication would be needed primarily for test and verification purposes, since operational downlinks are established in the Ka-band or X-band range.

The preferred wavelengths for future intersatellite and interorbit links are either in the 1550 nm range or in the 1064 nm range.

#### (2) Deep space missions

For deep space missions an optical downlink offers significant advantages.

Uplinks preferably are established by microwave (X- or Ka-band) transmitters, since low bandwidths are requested and link availability is not restricted by clouds. The downlink however may better be established by optical means, because payload volume and mass of the S/C will become considerably smaller, and high data rates can be handled. For deep space the wavelength of 1064 nm presently is the best choice.

Up to the Mars distance 34 Mbit/s (corresponding to HDTV standard) may be handled from ground by telescopes of the 1-m class. For distances beyond Mars a new class of 10-m telescopes is in the planning.







# 8 European Experiments

#### 8.1 AMSAT P3-D / AO-40

AMSAT is a private non-profit organisation which promotes the research, development and launch of communication satellites. P3-D denotes the third phase in a series of small communication satellites.



AMSAT P3-D (also named AO-40 "AMSAT Oscar 40") carries an infrared laser with which a downlink may be established from the apogee position.

The laser technical characteristics are as follows (AMSAT-DL 1/2000)

laser type	Siemens SFH 482403, IR laser diode, temperature stabilized	
wavelength	835 nm +/- 2 nm (TBC)	
laser power	peak: 500 mW; average: 250 mW @ 50% duty cycle	
beam divergence	1.2° (1/2000 sr ≈ 41 dBi antenna gain)	
	1000 km footprint at 50.000 km apogee height	
modulation	400 bps BPSK (1600 Hz square wave modulation)	
	this corresponds to the P3-D telemetry format	

The power link budget, assuming 70% atmospheric transmissivity and 10 cm receiver aperture diameter, leads to  $10^{-15}$  Watt received power (10 photons/bit @ 400 bit/s).

BPSK (binary phase shift keying) is the simplest way of phase modulation. For demodulation the carrier frequency and the correct phase must be known (because PSK needs a coherent demodulation scheme). In general, the carrier and phase can be gained at the receiver side by full-wave signal rectification and phase correction via COSTAS loop. Demodulation is achieved by a synchronous detector, or a standard phasedetector.

AMSAT Phase 3D was launched on November 16, 2000 into a geosynchronous transfer orbit (GTO) by an Arianespace launch vehicle (AR-507) from Kourou. Within a few hours after launch telemetry was being received from the 2 m beacon, but the 70 cm transmitter signal was not heard.

The official AMSAT report on the 12/2000 failure of AO-40:

Before the satellite could be regularly used it was necessary to carry out orbital changes, stabilize the satellite and open the solar panels. On the first attempt to fire the 400N



propulsion system it failed. On the second attempt the main solenoid did not shut of for 2 or 3 minutes, placing the satellite into a higher apogee orbit than was planned. Shortly afterwards a second anomaly occurred caused by fuel migration in the lines between isolation valve and the 400N motor.

On December 11, 2000, a sudden loss of signal occurred. Initial thoughts were that the spacecraft completely dead, with the possibility that AO-40 was in multiple pieces. After several attempts the S-band transmitter was successfully activated on December 24, 2000.

In the meantime the satellite could be stabilized by magnetorquers; spin rate is approximately 2 RPM; the orbit is stable now (20 years life orbit) with the perigee raised from 170 km to above 300 km. The three momentum wheels are operating properly and were tested up to 100 RPM, which means that the spacecraft has a working 3-axis control system. The open question still is the amount of remaining fuel; this will be clarified shortly by inertia measurement via activating the momentum wheels.

After a few more tests the spacecraft we will transferred from spin stabilization into 3-axis stabilization.

#### 8.2 SMART-1

#### a) Satellite

SMART-1 is a 'flexi-mission', the first one in the SMART (<u>Small Missions for Advanced</u> <u>Research in Technology</u>) Programme. The purpose of SMART is to test new technologies that will eventually be used on bigger projects.

The primary objective of SMART-1 is to flight test Solar Electric Primary Propulsion as the



key technology for future Cornerstones, e.g. the Bepi-Colombo mission to Mercury. Another objective is to test new technologies for spacecraft and instruments, one of which is the Laser-link experiment.

The planetary objective selected for the SMART-1 mission is to orbit the Moon for a nominal period of six months. It is the first time that Europe sends a spacecraft to the Moon.

The project aims to have the spacecraft ready in October 2002 for launch as an Ariane-5 auxiliary payload; launch date is scheduled for December 21, 2002.

Starting from GTO the new ion propulsion will spiral the satellite into a highly eccentric polar orbit and eventually after a 17 months trip to the moon. There it will orbit the moon in 200 - 400 km height.

On board is the AMIE camera, a miniature CCD-camera equipped with a focal plane filter mosaic of which one is dedicated to a laser-link experiment, and a low-power micro-DPU.



Although the camera is primarily intended for moon imaging it is well suited to act as the counterterminal to the OGS in the laser-link experiment.

#### b) Laser-link experiment

It is well known that the atmosphere's influence on laser beam propagation is very different for uplink and downlink, known as the "shower curtain effect". The influence of the atmosphere on optical beams in downlink direction can be monitored by observing stars, but its influence for the uplink direction can only be evaluated theoretically.

The SMART-1 Laser-link experiment is ideally suited to monitor the uplink effects of the atmosphere on a laser beam for various conditions (target spacecraft at varying distances from Earth, laser beam passing through different air masses due to changing height above horizon etc). The Laser-link experiment is an important contribution to optical communication for deep space.

For the SMART-1 experiment the wavelength of the Ti:Sapphire can be tuned to 847 nm, the same wavelength as used in the SILEX experiment. The output power of the laser then is approximately six Watts. The new laser transmission technique can produce four incoherent sub-aperture beams, allowing to compare the signal consistency for single beam and multiple beam links..

The Laserlink experiment will be performed by pointing the spacecraft's AMIE camera towards the Earth. Apart from a laser line filter which covers a section of the CCD imaging array of the camera, there is no specific Laserlink equipment aboard SMART-1.

Using the spacecraft's orbital co-ordinates or ephemeris with respect to stellar background (as seen in the field of view of the OGS telescope), the Tenerife station will aim the laser beam at the spacecraft. The laser will be just a pure carrier and it is not intended to transmit any actual information. The pointing accuracy required is < 10 microradians.

## 8.3 MEDIS

"SOLACOS" was the national German programme for optical communication in space. Based on coherent detection schemes in the wavelength range of  $1.06 \mu m$  all essential components were developed and successfully tested.

DLR intends to verify SOLACOS in space under the acronym of MEDIS with the following operational conditions: Two satellites in MEO (18 hour orbits) shall carry optical terminals to establish and maintain an inter-orbit link; they shall also be capable to communicate via optical links to Ground Stations and to LEO spacecraft, preferably the ISS.

Tx wavelength	1064 nm
Tx power	1 - 2 W
Tx / Rx aperture	10 cm
pointing accuracy	50 - 100 µrad
detection scheme	coherent
projected life	10 years

The technical data presently available are only tentative figures.

# **8** European Experiments

Although MEDIS is a national project it might be of interest for ESA to participate in this programme for the following reason:

The European part of the ISS is linked to the ground via ARTEMIS using the Ka-band. When COLUMBUS is fully operational the remaing life of ARTEMIS may be only 2 years. This means that after end-of-life of ARTEMIS COLUMBUS has to use the communication link via the US Data Relay Satellite and US law will be made applicable to all data via this channel. An autonomous European link beyond ARTEMIS is highly desirable. MEDIS may provide such a link with high data rate capability.

# 8.4 Alternative Applications / Darwin Precursor Experiments

The Kiepenheuer Institut für Sonnenphysik (KIS) is going to build a 1.5 m ceramic (C/SiC) telescope at Izana, close to the OGS. This telescope will be diffraction limited in the whole optical range of the spectrum, and it will be supplemented by adaptive optics to correct the wavefront errors caused by turbulent atmosphere.



Fig. 8-4: Gregor Solar Telescope

In case the OGS is equipped with a similar type of telescope and adaptive optics representative experiments for Darwin can be made in Izana. Presently, such experiments are planned to be performed at the VLT on Cerro Paranal, Chile.

## a) Observation Time

The VLT is very critical with respect to observation time. Therefore, such experiments must be planned very carefully and in the long term. The same experiments in Izana are far less critical because the OGS is under ESA's responsibility and the counterstation at the



Gregory Coudé Telescope (GTC) is a sun observatory which mainly used is during daytime; therefore plenty of observation time is available during nighttime.

## b) Risks and costs

The limited observation time and the large distance to VLT will make Darwin precursor experiments at VLT risky and expensive

## c) Schedule

The interferometer assembly (PRIMA) at VLT is still in a rudimentary planning phase. Neither schedule nor costs are fixed yet.

d) Suitability

If PRIMA becomes operational in due time and is usable for Darwin it is still PRIMA, designed for the VLT and not quite suitable for Darwin. The combination of OGS and GCT (Gregory Coudé Telescope) however may be designed exactly to the needs of Darwin.

# 9 Recommendations for the OGS

# 9.1 Forthcoming Programmes

All three optical ground stations presently conduct communication programs with laser diodes in the wavelength range between 780 nm and 870 nm. The OGS is well equipped for this first phase of laser communication experiments. Commonalties exist between the stations and international cooperation take place, e.g. the GOLD experiment between US and Japan, and the SILEX - LUCE connection via ARTEMIS and OICETS.

The next phase of US and Japanese optical space communication is oriented towards the ISS, the wavelengths for uplink and downlink are both switched to 1550 nm. Both programs: OCDHRLF by NASA and LCDE by NASDA are independent and do not have interconnections. ESA has not planned to participate in optical communication to ISS, and the OGS is not well suited for LEO communication.

For deep space optical downlinks only are of interest; from ground to space preferably microwave links are used. The favorite wavelength for optical downlinks from deep space is 1064 nm. The first request probably will arise with the forthcoming Mars missions. 1-m class telescopes on ground are attractive for the Mars distance because they allow data rates up to 34 Mbps (HDTV level). Beyond Mars distance the achievable data rate with 1-m telescopes becomes too low to be competitive to Ka-band links. 10-m class telescope therefore are in the planning of NASA's deep space network to extend optical downlinks to Jupiter, Saturn and Neptun distances.

For Mars as well as for outer planets a distributed network of ground stations will be necessary, and the European OGS on Tenerife will play an important role in this case.

In the following the recommended modifications to the OGS are given together with the respective rationale





1.) Prepoare to recieve AMSAT P-3D laser downlink signal

No hardware modifications are requested, receiver unit must be adapted to the modulation scheme of 400 bit/s, BPSK.

2.) Prepare for laser uplink to SMART-1

No hardware modifications are requested, tracking scheme must be adapted to the SMART-1 trajectory.

3.) Prepare for MEDIS

If MEDIS is kicked-off ESA is advised to consider its participation because MEDIS will establish an autonomous European downlink from ISS to ground. This link can either be used semi-operational - in parallel to the Ka-band link via ARTEMIS -, or operational in case MEDIS survives ARTEMIS. For MEDIS the whole transmit-receive assembly has to be changed.

4.) Prepare for Mission to Mars

This is the most attractive way to use the OGS for laser communication beyond SILEX. For Mars missions the whole transmit-receive assembly has to be changed.

## 9.2 Design Proposals

## 9.2.1 Downlink from AMSAT P-3D (OSCAR 40)

In principle, the existing equipment may be used for the AMSAT P-3D optical downlink. However, it is advised to optimize the receiver and to avoid unnecessary parts in the optical receiver train.

laser wavelength	835 nm - 2 nm spectral width
laser output power	250 mW average
	500 mW peak @ 50% duty cycle
polarization	linear (parallel to x-axis)
modulation	1600 Hz square wave carrier
	400 bps BPSK modulated
beam divergence (full angle)	x = 1/30 rad, $y = 1/50$ rad (elliptical)
	corresponding to 41 dBi antenna gain
effective footprint with AMSAT at 50.000 km	≈ 1000 km diameter
atmospheric transmission	70%
received signal at 0.1 m telescope aperture	approx. 10 photons/bit

In order to compare the data and determine the bit error rate, the telemetry blocks may be recorded, including the 16-bit CRC. For the S-band downlink, a standard software (e.g. p3telem from www.amsat.org or Thomas Sailer's modemp3d with a sound card) can be



used. For the optical downlink, the "front end" of one of the existing sound card programs, probably modemp3d, should be modified.

Since no optical transmit beam is involved the detection unit may be put directly into the Coudé focus (or the Cassegrain focus if accessible).

# 9.2.2 Uplink to SMART-1

#### The AMIE camera

Fig. 8.2-1 Focal plane filter of the AMIE camera

Filter #5 is matched with the OGS nominal uplink laser wavelength of 847 nm. The spectral bandwidth of the filter is 10 nm (FWHM).

#### OGS Laser Transmitter

The OGS laser transmitter and its optical train may be used "as is".



However, the laser modulation should be

adapted and optimised w.r.t. to the frame rate of the AMIE camera. In the GOPEX experiment (see chapt. 8.3) the shutter of the camera onboard Galileo could be controlled and regular strings of laser dots were recorded on the slowly turning S/C with a frame time of 800 ms and the TMF firing at 15 Hz and the SOR firing at 10 Hz.

The AMIE is expected to operate on a constant frame rate, e.g. 25 Hz. The OGS laser shall be pulsed at integer multiples of the frame rate (e.g. 50 Hz, 75 Hz etc.) to generate repetitive patterns on subsequent frames.

## Pointing and Tracking

In GTO SMART-1 can be acquired via the Maksutov viewing telescope and tracked by the implemented OGS star tracking system.

In HEO acquisition and tracking may be made in parallel a) via the viewing telescope and star tracking system, and b) by a "point and shoot" to the predicted orbit position.

In the moon orbit point and shoot algorithms shall be applied, with or without reference stars, depending on the findings during HEO tracking.

## Data Evaluation

Provided that SMART-1 AOCS data are well known and accessible during the uplink experiment several features may be extracted from the AMIE images:

- (1) Is the S/C hit at all deduced from recorded laser dots
- (2) How accurately is it hit deduced from the intensity and regularity of the recorded dots



(3) What is the influence of the atmosphere - deduced from stochastic changes of laser dots in subsequent frames

(4) What is the accuracy of tracking - deduced from systematic changes of laser dots in subsequent frames

The SMART-1 uplink experiment provides valuable information for future optical communication between ground and space because it gives insight in:

- atmospheric influences on optical uplinks at different elevation angles and distances
- pointing-tracking accuracy and repeatability
- dependability of shoot and track algorithms

# 9.2.3 Preparation for Mars Missions

#### **General Aspects**

From the present point of view optical ground stations will operationally be needed almost exclusively for planetary missions. High data rates in the downlink are requested from Mars and from outer planets. Rather small optical terminals onboard the S/C can establish HDTV-quality links (34 Mbps) communicating to 1-m class telescopes on ground for the Mars distance, and to 10-m class telescopes for the outer planets. This 10-m class telescopes are already in planning.

All deep space optical communication scenarios are based on the Nd:YAG laser wavelength and use direct detection schemes.

For the scope of link availability a distributed network of optical ground stations is mandatory. The OGS plays an important role in this scenario. An early preparation of the OGS for deep space missions will put the Agency in the position to take part and influence the planning of future programmes and verification experiments.

## OGS Upgrade for Mars Missions

To prepare the OGS for future Mars missions the station has to be complemented by a transmitter at 1064 nm, the respective receiver and optical train elements. Preferably, a separate 1064 nm transceiver unit is implemented in the OGS instead of supplementing the existing SILEX equipment. This allows higher flexibility and optimisation of each optical train to its respective wavelength.

The upgrade is not complicated since suitable Nd:YAG transmitters and receivers are commercially available off-the-shelf in Europe as well as in the US; the fine pointing mirror (FPM) and the transmit pointing mirror (TPM) may be duplicated from SILEX. All other optical elements are standard components with standard 1064 nm coatings.

A well-suited location for the 1064 nm equipment would be on the Coudé floor in between the North- and South-pillars of the telescope mount. The Nd:YAG transceiver may be connected to the optical train (through the evacuated feed-through to the telescope) by rotating the lower folding mirror by 90°, or by inserting a dichroic beamsplitter. The Coudé





focus then is switched towards the Nd:YAG equipment instead of towards the SILEX equipment.

#### OGS Extension for Deep Space Missions

The extension for deep space (i.e. for outer planets, asteroids, comets) is straight forward. The most important aspect is the downlink rate which possibly might afford larger telescopes. An upgrade of the OGS in this direction may be thought of when optical deep space networks are put in more concrete terms.

#### 9.2.4 Preparation for MEDIS

MEDIS is based on coherent detection schemes in the 1064 nm wavelength range. There are several good reasons for a communication link from OGS to MEDIS:

- a) the programme is under European control
- b) the OGS is perfectly suited for MEDIS acquisition and tracking
- c) the wavelength range is compliant with the optical train of the OGS
- d) the link can be operated semi-operational in up- and downlink, i.e. in parallel to the operational microwave link,
- e) the link may be switched to fully operational on request either to establish an additional autonomous link to the ISS besides ARTEMIS, or to extend the bandwidth of data transmission.

To prepare the OGS for MEDIS the station has to be complemented by a transmitter at 1064 nm, the respective heterodyne receiver and optical train elements. In any case, a separate transceiver unit has to be implemented in the OGS, because supplementing the existing SILEX equipment is not practicable due to the completely different detection

scheme. Adaptive optics may be implemented in the receiver path to improve the detection efficiency, but is not deemed necessary.

The upgrade is not very complicated provided that suitable Nd:YAG transmitters and receivers can be supplied by Bosch SATCOM or Contraves Space which are familiar with this type of free space laser communication. The fine pointing mirror (FPM) and the transmit pointing mirror (TPM) may be duplicated from SILEX. All other optical elements of the optical train are standard components with standard 1064 nm coatings.

The best-suited location for the coherent Nd:YAG transceiver again would be on the Coudé floor in between the North- and South-pillars of the telescope mount. The equipment may be connected to the optical train (through the evacuated feed-through to the telescope) by rotating the lower folding mirror by 90°, or by inserting a dichroic beamsplitter. The Coudé focus then is switched to the Nd:YAG equipment instead of to the SILEX equipment.

# 9.2.5 Participation in ISS Link Experiments

The communication links up to the ISS and down from the ISS are based on 1550 nm; the beacons needed at 980 nm (US terminal) and 680 nm (JEM terminal). This means, that the whole transceiver equipment, the beacon and practically all optical components in the optical train must be exchanged or supplemented in the OGS. Only the OGS telescope may be used for this purpose.

It is doubted that the rather high effort to modify the OGS for an ISS link experiment pays off, because the link availability to ISS is a) short, b) uncertain, and c) not under control of ESA. Furthermore, the ISS links are only extensions of experiments without operational functions.

Therefore, no design for OGS upgrading is presented.

# 9.2.6 Preparation for Darwin Precursor Experiments

## The small solution - OGS alone

The OGS may be equipped with a second telescope, preferably a 1.5 m ceramic telescope, diffraction limited in the whole visible spectrum - the same telescope as is now under construction for KIS at Tenerife.

The 1.5 m telescope may be fixed on the existing English mount, opposite to the 1-m telescope, replacing the counterweight. Both optical paths are fed in parallel to the Coudé floor, where they are combined. Practically all interference experiments and nulling may be tested on a smaller scale.

Adaptive optics would be nice, but is probably not necessary. The offset between both telescope axes is approximately 3 m. The major WFE from atmosphere is tilt which presumably is the same for the adjacent telescopes and needs not be corrected.

# Recommendations for the OGS



Two further changes of the OGS are necessary for the implementation of this solution:

**Optical Ground Station** 

(1) The dome must be reconstructed. The shutter of the dome is too narrow for two telescopes to be operated simultaneously.

(2) A derotator must be implemented in the optical train.

Fig. 9-1: Sketch of the 1.5-m telescope on the English mount

The big solution - connection of OGS and GCT

The most meaningful experiments for Darwin may be performed if the OGS is equipped with the additional 1.5-m telescope (on the English mount - opposite to the 1-m telescope) and this telescope is connected to the GCT 1.5-m telescope. The telescope diameters are the same as for Darwin, the separation of both observatories is representative for Darwin, the light sources are real stars.

In this big solution the OGS dome presumably needs not to be reconstructed since only one telescope, the 1.5-m telescope of the OGS, is used during observation.

The major changes are:

(1) Adaptive Optics (AO) is mandatory (the AO of the GCT may be duplicated),

(2) a vacuum tube is requested between OGS and GCT,

(3) the vacuum tube must contain either the interferometric equipment or a moveable retroreflector to compensate optical path differences.



Fig. 9-2 Interferometric connection between OGS and GCT

Iss.



# **OGS** Optical Ground Station

# 10 Abbreviations List

AMIE	Asteroid Moon micro-Imager Experiment
AMSAT	Radio Amateur Satellite Corporation
AO	Adaptive Optics
AO-40	Amsat Oscar 40
ARISE	Advanced Radio Interferometry between Space and Earth
BEP	Bit Error Probability
BER	Bit Error Rate
BPSK	binary (or "biphase") phase shift keying
CCD	Charge Coupled Device
CRL	Communications Research Laboratory (Japan)
DSN	Deep Spacce Network
FOCAL	Free-Space Optical Assessment Link (planned STS payload)
GEO	Geostationayr Orbit
GOPEX	Galileo Optical Experiment
GRIN	Graded Index
GTC	Gregory Coude Telescope
GTO	Geosynchronous Tranfer Orbit
HDTV	High-Definition Television
HEO	High Elliptical Orbit
ISS	International Space Station
JEM	Japanese Experiment Module (on ISS)
KIS	Kiepenheuer Institut für Sonnenphysik, Freiburg (Germany)
LCDE	Laser Comunication Demonstration Equipment (on ISS)
LCT	Laser Communication Terminal
LEO	Low Earth Orbit
LUCE	Laser Utilising Communication Experiment (on OICETS)
MEO	Medium Earth Orbit
OCD	Optical Communication Demonstrator
OCDHRLF	OCD High-Rate Link Facility
OCTL	Optical Communication Telescope Laboratory
OGS	Optical Ground Station
OICETS	Optical Inter-orbit Communication Engineering Test Satellite
RMS	Root Mean Square
RPM	Rounds per Minute
S/C	Spacecraft
SILEX	Semiconductor-Laser Intersatellite Link Experiment
SMART	Small Mission for Advanced Research in Technology
TMF	Table Mountain Facility, California (USA)
VLT	Very Large Telescope (on Cerro Paranal, Chile)
WFE	Wavefront Error